NRL Report 6967

Electroacoustic Transducers for a 10,000-psig Underwater Sound Transducer Calibration Facility for the Frequency Range 10 to 4000 Hz

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15 August 1969

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ABSTRACT

The design and construction of the terminal and source transducers, a reciprocal spherical piezoelectric ceramic transducer, and the probe hydrophones that are part of a new USRD measuring facility are described. The facility is used for the calibration of underwater sound transducers in the frequency range 10 to 4000 Hz at hydrostatic pressure to 10,000 psig and controlled temperature from 3 to 45°C. It operates on the principle of active-impedance termination in a rigid-walled, water-filled tube.

PROBLEM STATUS

This is an interim report on the problem.

PROBLEM AUTHORIZATION

NRL Problem S02-30

Project RF 05-111-401-4471

Manuscript submitted 1 May 1969.

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (continued)

ELECTROACOUSTIC TRANSDUCERS FOR A 10,000-psig
UNDERWATER SOUND TRANSDUCER CALIBRATION FACILITY
FOR THE FREQUENCY RANGE 10 TO 4000 Hz

INTRODUCTION

Increased use of electroacoustic transducers in oceanographic measurements and by deep-diving submersibles requires a calibration facility that can measure the acoustic behavior of tran ducers to be used at great depth and in a wide range of environmental conditions. The transducers described in this report are part of the new USRD System J, a rigid-walled, water-filled tube terminated at both ends with active transducers. The theory and its application have been reported by Bobber, Beatty, and Phillips [1-5]. Acoustic calibration measurements are made in the frequency range 10 to 4000 Hz at temperature from 3 to 45°C and hydrostatic pressure to 10,000 psig. Other NRL Reports discuss the theory and mechanical construction [6] and the electronic instrumentation [7] of the facility.

CALIBRATION METHODS

In general, two methods of calibration can be applied in System J: comparison and reciprocity. Comparison calibration measurements can be made in the presence of standing waves in the frequency range 10 to 500 Hz; both comparison and reciprocity measurements can be made from 500 to 4000 Hz, with active transducers used as terminal impedances in the chamber to provide plane, progressive waves. Illustrations from reference [4] are included here as Figs. 1 and 2 to show the configurations of the transducers for the two types of termination--single and double.

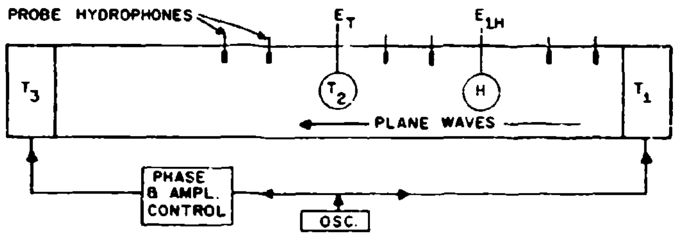

Fig. 1. Single-termination arrangement; T_1 is the source; T_3 is the terminal transducer; T_2 and H are unknown or standard transducers.

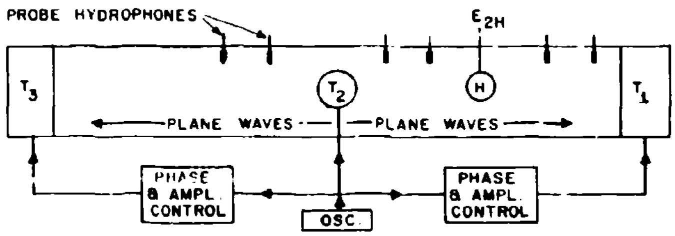

Fig. 2. Double-termination arrangement; T_2 is the reciprocal transducer; T_1 and T_3 are terminal transducers; H is the hydrophone in a reciprocity calibration.

In the single-termination arrangement, Fig. 1, when the phase and amplitude of T_1 are adjusted properly with respect to those of T_3, plane progressive sound waves produced by T_1 advance along the channel; energy reaching the end of the channel is absorbed or dissipated, instead of being reflected. The sensitivity of the unknown transducer is determined by comparison of its output with that of a standard hydrophone.

A reciprocity calibration requires use of both of the termination arrangements. For the case of double termination, Fig. 2, the source T_2 radiates plane waves in both directions; T_1 and T_3 act as absorbers. When the unknown transducer does not satisfy the conditions required of a reciprocal transducer, it must be used as the hydrophone; the USRD type F40J transducer developed for the purpose then serves as the reciprocal transducer.

SYSTEM TRANSDUCERS AND HYDROPHONES

System J requires three sound sources and a number of probe hydrophones. The source and terminal transducers shown in Fig. 3 consist of PZT-4 ceramic disks driving magnesium front plates. These transducers are identical; only the method of mounting them within the chamber is different. Figure 4 shows the reciprocal transducer, a ceramic sphere that is placed between the other two transducers during reciprocity measurements. Six probe hydrophones are available for monitoring the sound field while the conditions for a plane, progressive wave within the water-filled channel are being established. Three hydrophones and their supports are shown in Fig. 5.

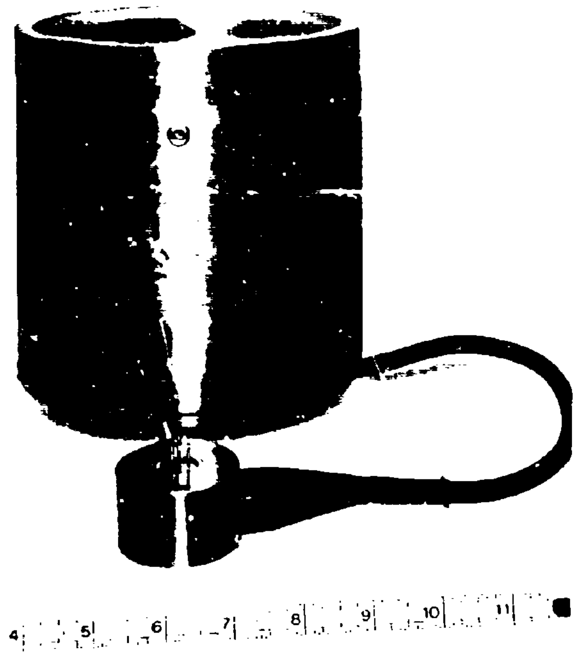

Fig. 3. USRD type G23J source and terminal transducer.

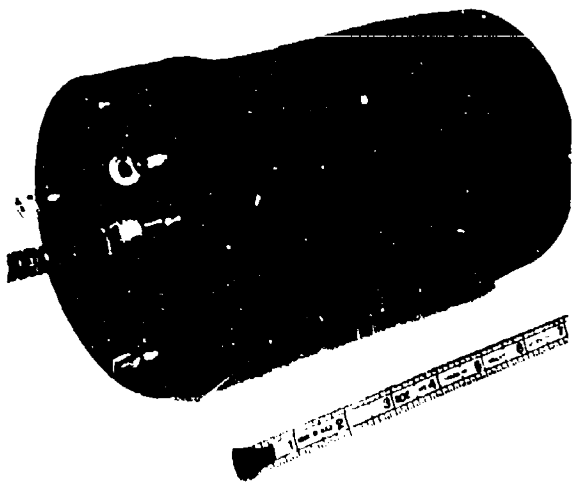

Fig. 4. USRD type F40J ceramic sphere reciprocal transducer.

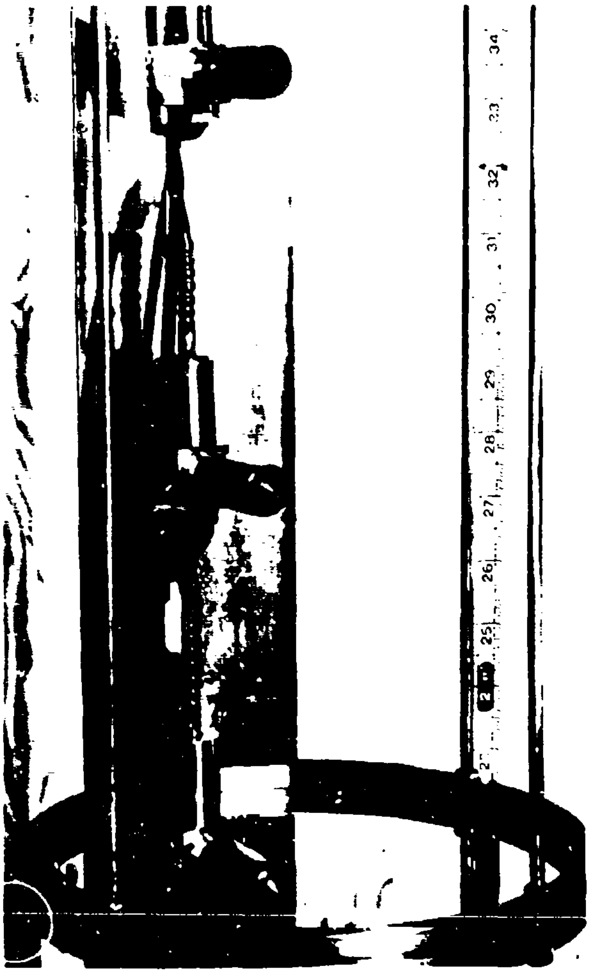

Fig. 5. USRD type A40 high-pressure probe hydrophones on support frame.

GENERAL REQUIREMENTS

The stated design goals for the transducers and probe hydrophones were as follows:

1. All system transducers and hydrophones to operate at pressure to 10,000 psig and temperature from 3 to 45°C with little change in acoustic characteristics.

2. Source transducers to operate in the frequency range 10 to 4000 Hz; change in transmitting response with temperature to be less than 0.01 dB/°C; change with static pressure to be less than 0.001 dB/psi; transducers to be self-compensating for hydrostatic pressure; motion of the radiating surface to be as nearly that of a piston as possible.

3. Reciprocal transducer to obey the reciprocity principle throughout the frequency range 400 to 4000 Hz, and its sensitivity to be as high as possible at the low frequencies.

4. Probe hydrophones to be as small as possible; all parts of the housing and cable to be acoustically stiff, or transparent; long-time stability to be maintained.

DETAILS OF SYSTEM J TRANSDUCERS

Projectors, or Source Transducers

Design. The basic design of the USRD type G23J transducers is the same as that of the type G16 used in the high-pressure, Long-Tube Facility [4]. Only the dimensions of the transducers, the size and number of crystals, and the operating frequency range are different. The active element consists of 7 stacks of 10 each 5.08-cm-dia PZT-4 ceramic disks 6.35 mm thick, connected electrically in parallel. The nominal capacitance of each disk is 3200 pF, making the total capacitance about 0.225 μF. The transducer is filled completely with Dow Corning 220 silicone fluid, thus eliminating the need for a seal around the magnesium plate with its attendant shear losses [8]. The stability under hydrostatic stress with this construction is much better than that of designs in which the piezoelectric material is subject to one- or two-dimensional stress [9,10]. The rear mass is of 7.62-cm-thick stainless steel and the 15.875-cm-dia front plate is of magnesium 2.54 cm thick. Construction details* are shown in Fig. 6.

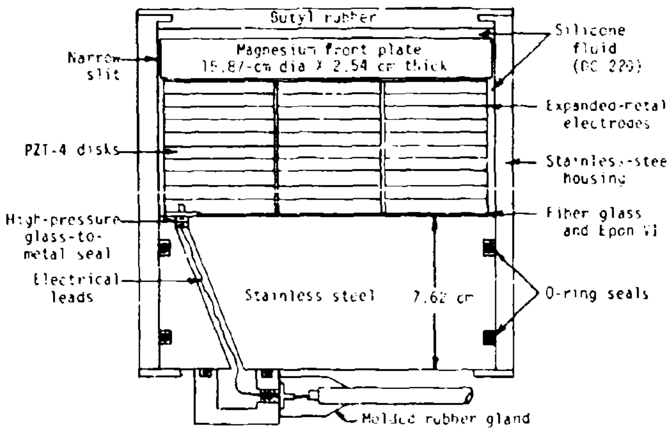

Fig. 6. Construction details, type G23J transducer; sensitive element consists of 70 ceramic disks 5.08 cm in diameter and 6.35 mm thick arranged in 7 stacks.

*Detailed drawings have been made for the G23J Transducer. A complete list of drawing numbers is provided on USRD assembly drawing CM2311.

The piezoelectric disks in each stack are bonded together with Epon VI epoxy. They are polarized and driven in the direction parallel to the cylindrical axis of the stack. Preformed pieces of expanded nickel sheet that has been flattened to 0.05 mm thickness are inserted between the disks to provide contact with the fired-silver electrodes on each ceramic element. This sheet also determines the minimum thickness of the cement interface. The ceramic stacks are insulated at each end by two layers of fiber glass and Epon VI epoxy, which also serves as an intermediate layer between the ceramic and the front and rear masses and reduces the probability of failure of the bond because of differences in the thermal coefficients of expansion of magnesium, ceramic, and steel. (The strength of the transducer depends only upon the cement bond; the construction does not include a mechanical bias bolt commonly found in some longitudinal vibrators.) A small portion of the six outer ceramic stacks is ground away so that the diameter of the housing can be made as small as possible. This, and other details of the assembly can be seen in Fig. 7.

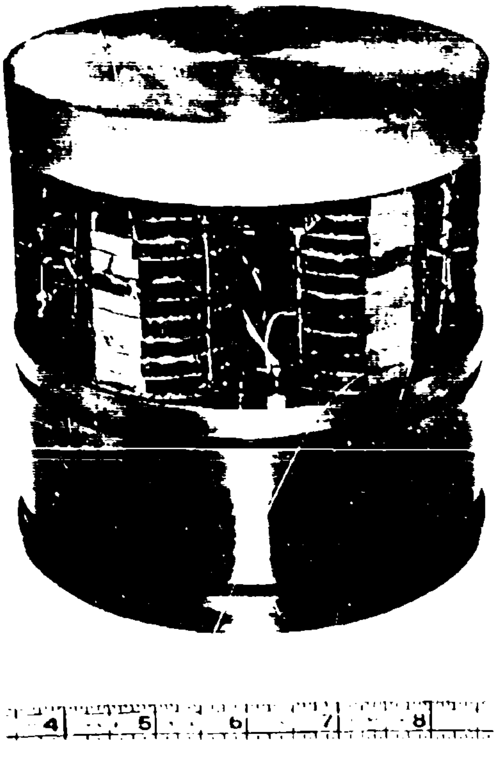

Fig. 7. Type G23J transducer with case removed, showing front plate, piezoelectric ceramic stacks, and rear mass.

The slit between the magnesium front plate and the steel housing has been kept small to maintain high acoustic impedance. Initial calibration measurements revealed that the acoustic pressure from the transducer decreased at frequencies below 15 Hz. Computation indicated that the slit impedance was too low. To correct this condition, a metal shim

0.05 mm thick was inserted into the slit of the first transducer. The need for the shim has been eliminated in later models by holding the dimensions to closer tolerance.

Applied voltages of 800 to 850 V (rms) produce the required sound-pressure levels at frequencies below 150 Hz. The computed sensitivity and other design considerations are given in Appendix A.

Acoustic Characteristics. Table 1 shows the free-field voltage sensitivity of three type G23J transducers calibrated in open water and in the Long-Tube Facility. The change in sensitivity with pressure to 8500 psig is within the design specification.

Table 1

FREE-FIELD VOLTAGE SENSITIVITY
(Decibels re one volt per microbar)

G23J Transducers
Open-circuit voltage at end of 10-ft cable
Unbalanced: black lead and shield grounded
Water temp: 27°C

(Read all sensitivity values as negative)

Freq (Hz)	Serial 7		Serial 8		Serial 9	
	0 psig*	8500 psig	0 psig*	8500 psig	0 psig*	8500 psig
100	97.8	98.4	97.8	98.4	97.6	98.4
200	97.8	98.4	97.8	98.4	97.6	98.6
300	97.8	98.5	97.8	98.4	97.6	98.7
400	97.8	98.5	98.1	98.7	97.6	98.7
500	98.3	98.8	98.2	98.7	97.7	98.7
600	98.3	98.8	98.2	98.8	97.7	98.7
700	98.3	98.8	98.2	99.3	97.7	98.7
800	98.5	98.8	98.2	99.5	98.0	99.0
900	98.5	99.1	98.2	99.5	98.5	99.3
1000	98.7	99.1	98.2	99.5	98.6	99.4
1100	98.7	99.4	98.2	99.6	98.6	99.4
1200	99.0	99.4	98.2	99.6	98.7	99.4
1300	99.0	99.6	98.4	99.6	98.7	99.5
1400	99.2	100.0	98.4	99.7	98.7	99.9
1500	99.4	100.0	98.8	99.8	98.8	99.9

*Before and after pressure.

Impedance was measured in System J at the temperatures 5 and 25°C and the hydrostatic pressures 100, 500, and 10,000 psig. Magnitude of the impedance is shown in Fig. 8. Measurements at each frequency were made with the terminal transducer adjusted for proper termination of the chamber.

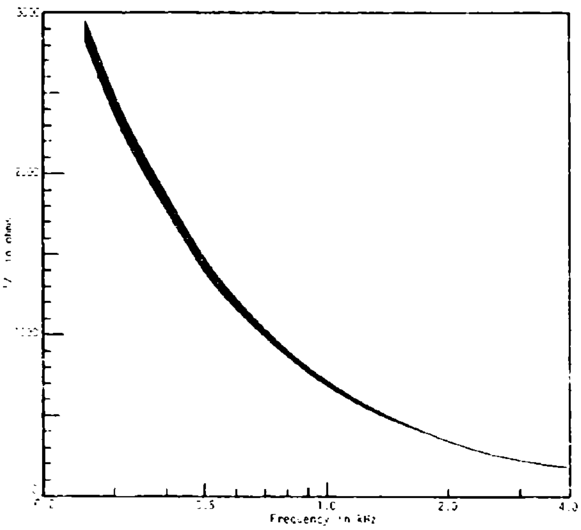

Fig. 8. Range of magnitude of impedance, type G23J transducer.

Reciprocal Transducer

Design. The third transducer, required for reciprocity measurements, is a 10.16-cm-dia piezoelectric, lead zirconate - lead titanate, hollow sphere mounted within a castor-oil-filled butyl boot. The principal features are shown in Fig. 9. To minimize the effect of hydrostatic pressure on sensitivity, the sphere is free flooding. The 1.9-cm-dia access hole in the 6.35-mm-thick ceramic wall is covered by a ceramic disk bonded in place with Hysol epoxy cement. A 5.05-mm-dia orifice in the center of the disk admits the castor oil and permits the hydrostatic pressure to equalize within the sphere. The low-frequency rolloff in sensitivity is determined largely by the diameter of this small hole. The Helmholtz resonator principle acts here to enhance the low-frequency sensitivity of the transducer; the low-frequency resonance is determined primarily by the size of the opening and the volume of the cavity. These design considerations are discussed in Appendix B.

Electrical connection to the transducer is made through a 2-conductor, shielded, blocked (nonhosing) cable entering the housing through a swaged cable seal. The cable is terminated in a USRD-designed, high-pressure, molded gland with an O-ring seal.

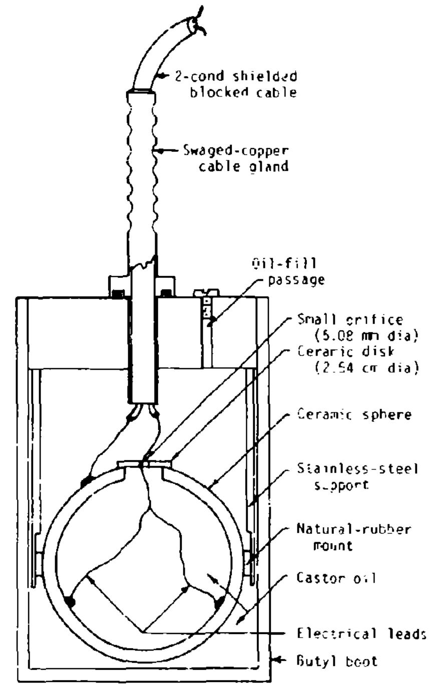

Fig. 9. Construction details, type F40J transducer. Sensitive element is lead zirconate - lead titanate sphere 10.16 cm dia with 6.35-mm wall and fired-silver electrodes.

Acoustic Characteristics. The pressure-compensated USRD type F40J has been calibrated at the temperatures 5, 20, and 40°C. The sensitivity did not change except in a narrow region near 500 Hz, where the low-frequency rolloff starts. It is believed that the change in viscosity of the castor oil is responsible for this change. Sensitivities measured by the Lake Facility and in Low-Frequency System J between 350 and 4000 Hz are almost identical. The free-field voltage sensitivity from open water and System J measurements in shown in Fig. 10. Transmitting current response is shown in Fig. 11.

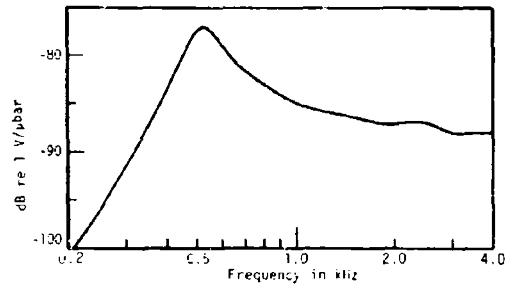

Fig. 10. Free-field voltage sensitivity, type F40J reciprocal transducer.

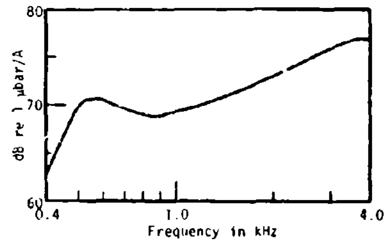

Fig. 11. Transmitting current response, type F40J transducer.

Probe Hydrophones

Design. Because stability of the probe hydrophones is of prime importance, lithium sulfate crystals were selected for the sensitive element. This material has been used at the USRD for 20 years in the construction of standard hydrophones and projectors to be used at high hydrostatic pressure. Furthermore, the characteristics of lithium sulfate have been studied in the USRD high-pressure coupler to 16,000 psig [11]. The property of retaining high sensitivity, even when all surfaces of the crystal are exposed to the sound pressure, eliminates the need for pressure-release material. To insure acoustically stiff construction, the preamplifier is contained in a tubular, stainless-steel housing, and the cable sheath and dielectric are of solid rubber. All voids are filled with Epon 828 epoxy to prevent movement or the possibility that the fluid under high pressure can force the cable into the housing.

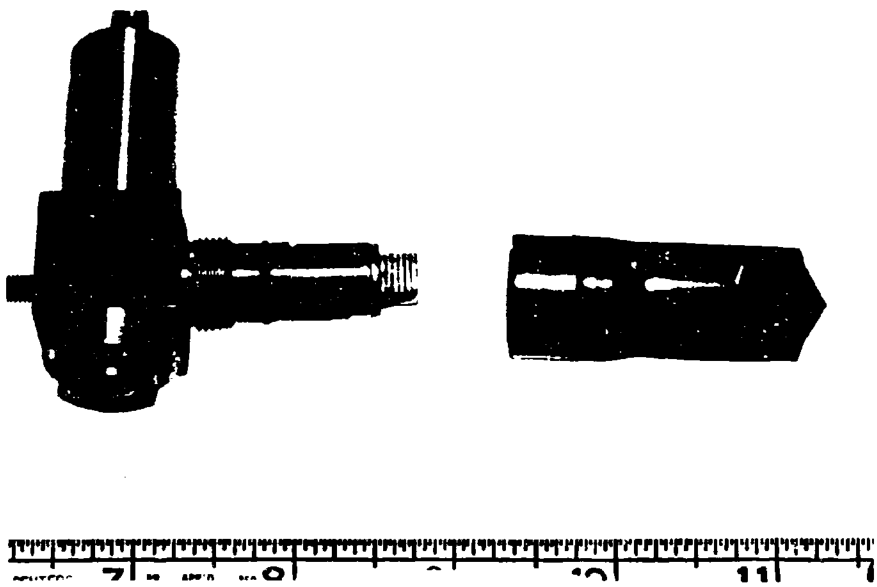

Fig. 12. Type A40 probe hydrophone with boot removed.

The simplicity of design of the USRD type A40 probe can be seen in Fig. 12. Figure 13 shows the construction features. Each probe hydrophone contains six lithium sulfate 0°, Y-cut crystals 6.35×6.35×1.02 mm bonded together with Vulcalock, a rubber-base cement. The electrodes are made of 0.0254-mm-thick gold-plated silver foil. Small tabs on each electrode foil enable all crystals to be connected electrically in parallel. The leads from the crystal stack are connected to miniature high-pressure glass-to-metal seals. The stack is cemented to a small cylindrical slug of tungsten, which, in turn, is cemented to the steel housing. A thin fuzed-quartz plate separates the crystal stack from the metal and provides high electrical resistance to ground. To maintain long-time stability,

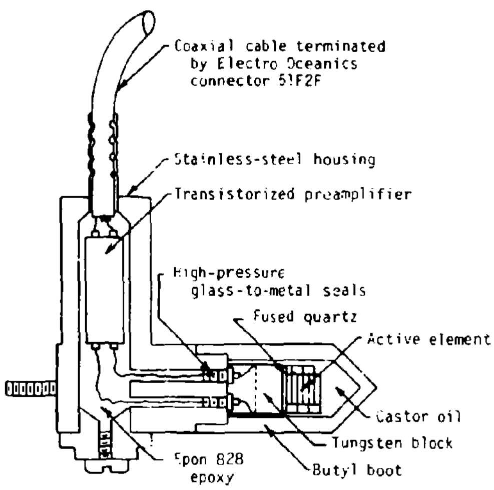

Fig. 13. Construction details, type A40 probe hydrophone. Sensitive element consists of six lithium sulfate crystals 6.35×6.35×1.02 mm.

the crystals are protected from water by a thin butyl rubber boot filled with vapor-free castor oil.

Even a minute quantity of water vapor increases the surface leakage of the water-soluble lithium sulfate element and reduces its sensitivity at low frequencies. The permeability of butyl rubber to water is very low; in this respect, butyl is superior to natural rubber, polyurethane, and neoprene compounds. A. Lebovits [12] has reported that the permeability of elastomers such as butyl does not increase at high hydrostatic pressure. Extensive use of butyl compounds for acoustical boots has proven their ability to protect the crystals adequately for a long time.

Some models of the A40 probe contain an expanded-metal shield just inside the boot, as shown in Fig. 14, to provide electrostatic shielding

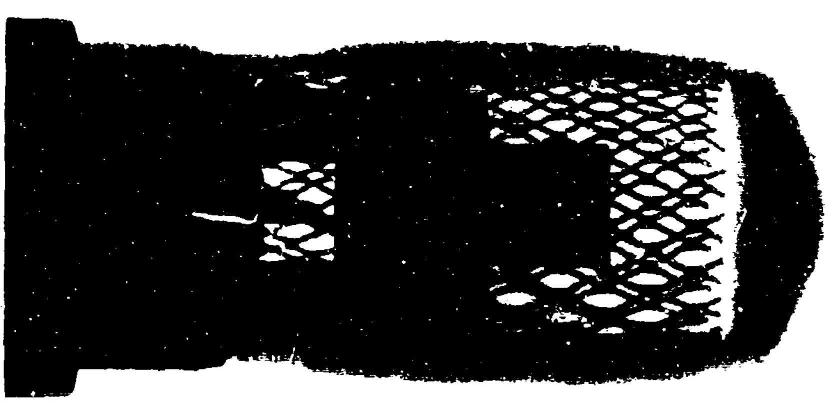

Fig. 14. X-ray photograph, type A40 probe hydrophone, showing expanded-metal shield around the crystals and crystal mounting.

for the high-impedance crystal. The shield has been omitted in the construction of later models, because it has been found that it is not required in System J.

The output voltage of the crystal element is applied directly to the first-stage transistorized preamplifier, which provides a high-impedance input (1000 MΩ) and low-impedance output. One coaxial cable carries the output signal and the power required for the preamplifier. A commercially available Electro-Oceanics 51F2F connector mates the cable with the electrical bulkhead connector mounted on the top tank closure. The bulkhead connectors and the outside coaxial connectors can be seen in Fig. 15.

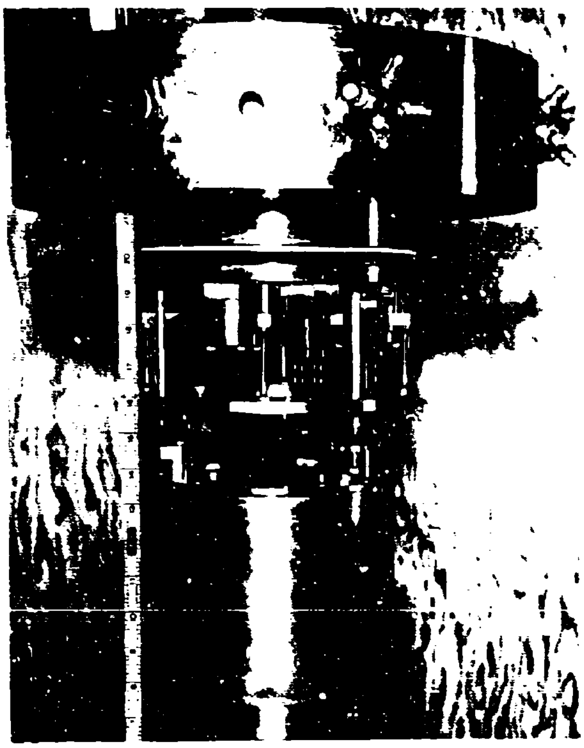

Fig. 15. Top closure plate of System J, showing both internal and external probe hydrophone connectors, and type G23J source transducer mounted.

Acoustic Characteristics. As measured in open water and in the closed systems, the free-field voltage sensitivity at the output of the preamplifier is -100 dB re 1 V/μbar from 10 to 4000 Hz. Sensitivity does not change at any pressure from 0 to 10,000 psig.

ACKNOWLEDGMENTS

The authors express appreciation to R. J. Kieser and A. C. Tims for their contributions to the design and their attention to the details of construction. Thanks go also to Leader John Heins and the other USRD machinists for their precision workmanship.

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Appendix A

CALCULATION OF SENSITIVITY
TYPE G23J TRANSDUCER

The open-circuit voltage sensitivity of the G23J transducer at low frequencies depends upon the piezoelectric constants g_{33} and g_{31}, the thickness of the ceramic disk, the ratio of the diaphragm area to the cross-sectional area of the ceramic, the slit impedance, and the compliance of the fluid volume within the transducer.

If the transducer were free flooding, the open-circuit voltage sensitivity would be only that due to the volume sensitivity of the ceramic:

$$M_{oc} = (g_{33} + 2g_{31})t,$$

where t is the thickness of one disk. The impedance of the slit effectively blocks the sound pressure from the inside of the transducer, however, so that the sensitivity approaches the value

$$M_{oc} = (A_1/A_2)g_{33}t$$

where A_1 is the diaphragm area and A_2 is the cross-sectional area of the ceramic.

The effect of slit impedance can be seen more clearly from the equivalent circuit, Fig. A1. The acoustic impedance of the slit [A1] is

$$Z_s = R_s + jX_s = 12\eta\ell/t^3w + j(6\rho\ell\omega/5wt), \qquad \text{(A1)}$$

where η is the dynamic viscosity of the fluid, ℓ is the depth of the slit, t is the width of the slit, w is the slit dimension perpendicular to the direction of the sound wave, and ρ is the density of the fluid.

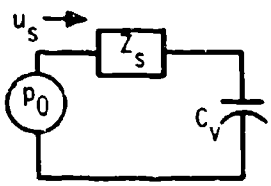

Fig. A1. Equivalent circuit, slit impedance of type G23J transducer; u_s is the volume velocity in the slit; Z_s and C_v are defined in Appendix A.

For DC 220 fluid, $\rho = 1.034$ kg/m^3 and $\eta = 0.442$ Nsec/m^2; from Eq. (A1), $Z_s = 1.310\times10^8 + j0.494\times10^4$ Nsec/m^5.

The acoustic compliance [A2] of the fluid volume contained between the front and rear masses is

$$C_v = V/\rho c^2, \qquad \text{(A2)}$$

where V is the volume and c is the sound speed in the fluid. For DC 220 fluid, c = 1164 m/sec. From Eq. (A2), C_v is 0.253×10^{-6} m^5/N.

The ratio of the sound pressure developed in the fluid volume to that at the diaphragm is

$$p_v/p_0 = |Z| \cos \theta ,$$

where $|Z| = [(1-\omega^2 X_s C_v)^2 + (\omega R_s C_v)^2]^{-\frac{1}{2}}$, and $\theta = \tan^{-1}[\omega R_s C_v/(1-\omega^2 X_s C_v)]$.

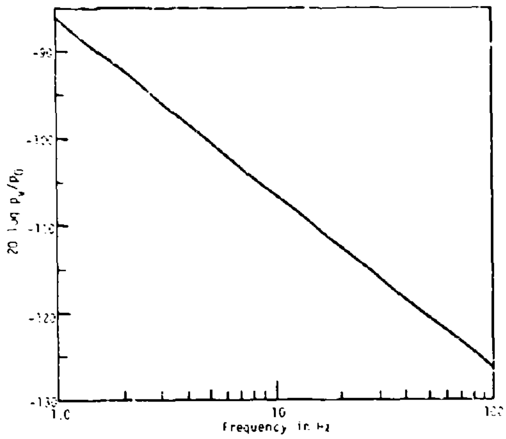

Fig. A2. Ratio of sound pressure developed in the fluid volume to that at the diaphragm, type G23J transducer.

Figure A2 shows the plot of 20 log p_v/p_0 from 1 to 100 Hz. The phase angle θ remains virtually -90°. From this, it can be seen that the sound pressure at the diaphragm is blocked from the inside of the transducer, except at very low frequency.

If the effect of the slit is neglected, the expression for the open-circuit voltage sensitivity is

$$M_{oc} = (A_1/A_2)g_{33}t,$$

the computed value for which, in this case, is -93.8 dB re 1 V/μbar. This value is about 2 dB higher than that measured. To resolve the discrepancy, the effective electromechanical voltage constant g_{33} for the composite transducer was measured as follows:

The transducer (without oil) was set on its rear mass with the magnesium diaphragm facing upward. A known mass was placed on the diaphragm and the electrical terminals of the transducer were first shorted, then connected to the input of an electrometer. When the mass was removed, the resulting voltage was read from the electrometer. From this measurement, d_{33} was computed. Then, from the relation: $g_{33} = d_{33}/\varepsilon$, where ε is the dielectric constant for the ceramic, the new value 19.3×10^{-2} Vm^{-1}/Nm^{-2} was obtained for g_{33}, which yields the value -95.4 dB re 1 V/μbar for the open-circuit voltage sensitivity. The cause of the remaining difference between measured and computed sensitivities shown in Fig. A3 has not been determined completely. Above 1000 Hz, diffraction effects and the

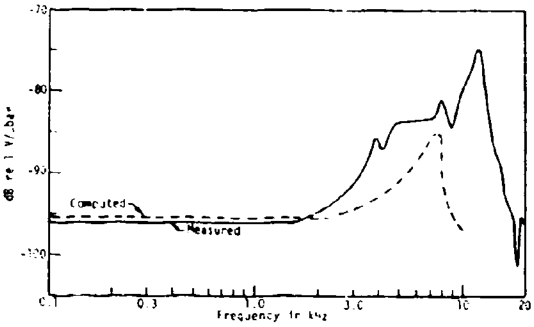

Fig. A3. Free-field voltage sensitivity, type G23J transducer.

resonance of the ceramic with the diaphragm and water load cause the sensitivity to rise.

An equivalent circuit that approximates the transducer is shown in Fig. A4. The fundamental plate resonance of the magnesium diaphragm occurs at about 12 kHz. This plate resonance seems to dominate the mechanical resonance predicted by the equivalent circuit.

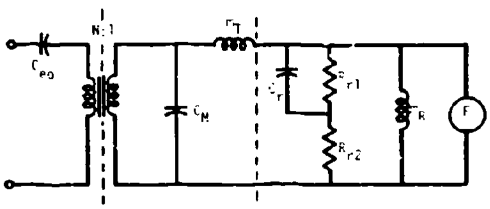

Fig. A4. Simplified equivalent circuit, type G23J transducer. Symbols are defined in Appendix A.

The values used in the computations are:

Symbol	Description	Value	Unit
C_{eo}	Electrical capacitance well below resonance	0.225×10^{-6}	F (measured)
N	Electromechanical transfer ratio	0.0089	V/N
C_M	Mechanical compliance of ceramic stack	69.3×10^{-12}	m/N
m_t	Effective mass, ceramic and magnesium diaphragm	4.904	kg
C_r	Capacitive part of radiation load	3.07×10^{-9}	F
R_{r1}	Resistive component of radiation load	14,900	Ω
R_{r2}	Resistive component of radiation load	29,700	Ω
m_r	Mass of water load	0.965	kg

References

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[A2] Reference [A1], pp. 121-127.

Appendix B

ANALYSIS OF F40J TRANSDUCER

The F40J transducer is a 4-in.-dia (approx) hollow piezoelectric ceramic sphere with a 0.25-in.-thick wall. The sphere is mounted in a rubber boot completely filled with castor oil, which floods the interior of the sphere through a hole in its shell. The sphere acts as a Helmholtz resonator at a frequency determined by the size of the hole and the volume of castor oil in the sphere.

An equivalent circuit whose response approximates that of the transducer is shown in Fig. B1. Use of the equivalent circuit enabled the size of hole to be chosen so as to place the Helmholtz resonance in the most desirable frequency range.

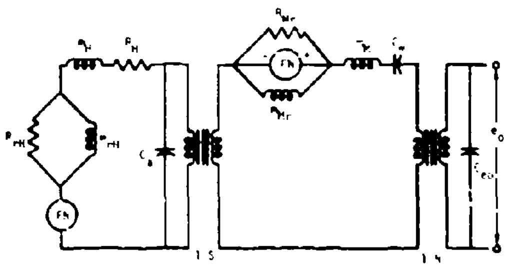

Fig. B1. Simplified equivalent circuit, type F40J transducer. Symbols are defined in Appendix B.

Figure B2 shows a comparison between the sensitivity of the equivalent circuit as computed with a digital computer and that of the transducer as measured in System J. A description of the circuit components, values, and units follows.

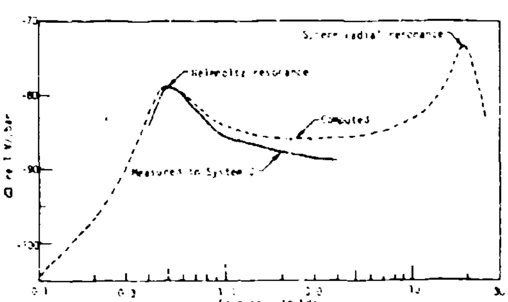

Fig. B2. Free-field voltage sensitivity, type F40J transducer.

Symbol	Description	Value	Unit
F	Force acting on sphere due to sound pressure		N
N	Electromechanical transfer ratio	0.0569	V/N
S	Area of inside of shell	2.489×10^{-2}	m^2
R_{rH}	Radiation resistance from the hole	104.6×10^{9}	Nsec/m
m_{rH}	Radiation mass at the hole	0.152	kg
m_H	Acoustic mass of fluid in the hole	39.9×10^{4}	kg/m^4
R_H	Acoustic resistance of fluid in the hole	74.7×10^{7}	$Nsec/m^5$
C_A	Mechanical compliance of fluid in the sphere	1.79×10^{-13}	m/N
R_{Mr}	Radiation resistance of sphere	4.80×10^{4}	Nsec/m
m_{Mr}	Radiation mass of sphere	1.64	kg
m_M	Mass of ceramic shell	1.56	kg
C_M	Mechanical compliance	0.067×10^{-7}	m/N
C_{eo}	Electrical capacitance well below resonance	0.047×10^{-6}	F
e_0	Open-circuit output voltage		V

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)

Naval Research Laboratory
Underwater Sound Reference Division
P. O. Box 8337, Orlando, Florida 32806

2a. REPORT SECURITY CLASSIFICATION

UNCLASSIFIED

2b. GROUP

3. REPORT TITLE

ELECTROACOUSTIC TRANSDUCERS FOR A 10,000-psig UNDERWATER SOUND TRANSDUCER CALIBRATION FACILITY FOR THE FREQUENCY RANGE 10 TO 4000 Hz

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

An interim report on the problem

5. AUTHOR(S) (First name, middle initial, last name)

Ivor D. Groves, Jr., and Theodore A. Henriquez

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
15 August 1969	22 + iii	14

8a. CONTRACT OR GRANT NO.

NRL Problem S02-30

b. PROJECT NO.

RF 05-111-401-4471

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)

NRL Report 6967

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

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11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY

Department of the Navy
(Office of Naval Research)
Washington, D. C. 20360

13. ABSTRACT

The design and construction of the terminal and source transducers, a reciprocal spherical piezoelectric ceramic transducer, and the probe hydrophones that are part of a new USRD measuring facility are described. The facility is used for the calibration of underwater sound transducers in the frequency range 10 to 4000 Hz at hydrostatic pressure to 10,000 psig and controlled temperature from 3 to 45°C. It operates on the principle of active-impedance termination in a rigid-walled, water-filled tube.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Technical facilities						
Transducers - Test facilities						
Transducers - Calibration						
Electroacoustic transducers - Design						
Impedance tubes						
Probe hydrophones						
Low frequency						
High pressure						
Pressure vessels - Equipment						

AD-693051

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28 October 1969

NOTICE to all holders of NRL Report 6967, "Electroacoustic Transducers for a 10,000-psig Underwater Sound Transducer Calibration Facility for the Frequency Range 10 to 4000 Hz," by Ivor D. Groves, Jr., and Theodore A. Henriquez:

Figure B1, Appendix B, page 18 of the subject report is incorrectly drawn. Please correct it to conform with the revised Fig. B1 shown below.

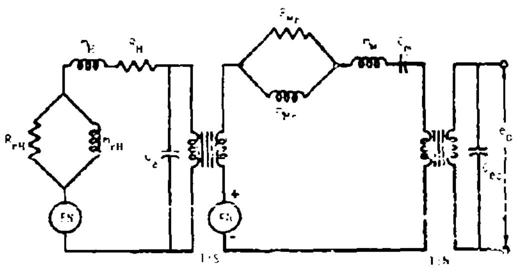

Fig. B1.